Estimating Flow Discharge for Select Passages in Mammoth Caves Based on Analysis of Scallop Lengths and Passage Areas

A Thesis

Presented in partial fulfillment of the requirements
for the degree of Bachelor of Science
in Geological Sciences

By

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Abstract

The purpose of this study is to estimate the flow discharge for select cave passages in the Mammoth Cave System. This is done in two steps. First, peak flow velocity is calculated using scallop length measurements and a graph based on the equations of Curl (1974), which yield the average flow velocity of a rectangular or circular passage. Next, a cross section of the specific cave passage is measured using a laser distancemeter and a measuring tape. From these measurements, the cross-sectional area of a cave passage can be calculated. These data can then be combined with the flow velocity data to estimate the peak flow discharge of the cave passage. Mean scallop lengths range from 10 to 72 cm. Passage areas range from 13 to 590 ft^2. Estimates of mean discharge range from 12 to 649 ft^3/sec. Analysis of these data shows that passage areas decrease downstream, suggesting a similarity to a distributary channel system. Data also suggest that as passage area decreases, mean water velocity increases. To eliminate sampling bias from too few measurements, it is suggested more data be collected.

Acknowledgements

I would like to thank my family and friends for their continued support throughout my college career. I would also like to thank my classmates in Earth Science 670 for all their assistance in collecting the data. I could not have done any of this without you. Finally, I would like to thank Dr. E. Scott Bair for his guidance, support and encouragement throughout this project.

I. Introduction

1.1 Introduction

Mammoth Cave National Park is in west-central Kentucky. Its location can be seen on the map in Figure 1. The park occupies an area of more than 50,000 acres. The area was established as a National Park on July 1, 1941. With more than 325 miles of explored passages, Mammoth Cave is by far the longest cave in the world (Harris et. al. 2004).

Mammoth Cave lies under Mammoth Cave Ridge. To the north east is Flint Ridge. This ridge also holds vast expanses of caves. Cave explorers have long sought a connection between the caves of Mammoth Ridge and those of Flint Ridge. In 1972, a group of cavers from the Cave Research Foundation embarked on an expedition to find the connection. Entering the Austin Entrance in Flint Ridge, they traversed over 10 miles of some of the most difficult caving in the world. Pat Crowther, a small, young woman, pushed herself through The Tight Spot, a previously impassable section of cave. On the other side, she discovered water flowing west toward Mammoth Cave. This discovery led to further exploration. On September 9, 1972, a connection between the two was finally made (Brucker et. al. 1976). The team from the Cave Research Foundation expanded the length of the cave to more than 144 miles. They documented beyond reasonable doubt that Mammoth Cave is the world's longest cave (Wallace, 1998).

Exploration of Mammoth Cave is not a recent endeavor. From 3,000-4,000 years ago Native Americans explored the caves. They not only used the cave for shelter, but also collected minerals for medicine and flint for tools from deep within the cave. Just prior to 1800, white settlers rediscovered the cave. Salt peter was mined from the cave to make gunpowder. The gunpowder played an important role in the War of 1812. Shortly after the war, Stephen Bishop, a black slave, became one of the first tour guides. He also made many discoveries within the caves and gave some of the names to features that are still used today. In 1908, a young German named Max Kaemper came to Mammoth Cave to survey it for the first time. He surveyed over 45 miles of cave passages (Brucker et. al. 1976). Kaemper's 1908 map of Mammoth Cave can be seen in Appendix C. Since that time, countless research expeditions have been carried out to increase the understanding of the cave and its surroundings.

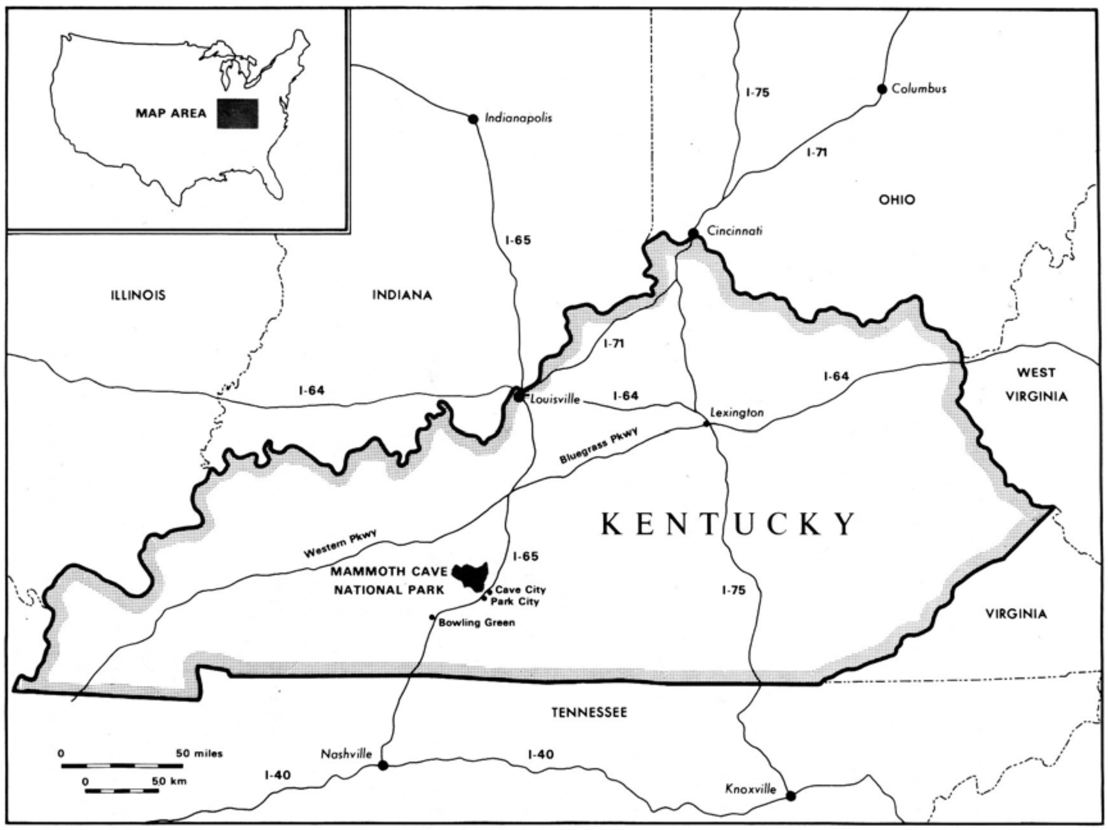

Figure 1. Map of Kentucky and surrounding states showing the location of Mammoth Cave National Park (Palmer, 2002).

1.2 Purpose and Scope

The purpose of this study is to estimate the flow discharge for select cave passages in the Mammoth Cave System. This is done in two steps. First, peak flow velocity is calculated using scallop length measurements and a graph based on the equations of Curl (1974), which yield the average flow velocity of a rectangular or circular passage. Next, a cross section of the specific cave passage is measured using a laser distancemeter and a measuring tape. From these measurements, the area of the cave can be calculated. These data can then be combined with the flow velocity data to attain the peak flow discharge of the cave passage. While it is interesting to note all the human history of Mammoth Cave and admire the magnificent speleothems lining sections of the caves, the measurements made for this research are aimed at leaning more about the paleohydrology of the cave system.

II. Geologic Setting

2.1 Stratigraphy

To understand the caves of the Mammoth-Flint Cave System, the rocks in which they are formed must first be understood. The rocks of Mammoth Cave National Park were deposited roughly 300 million years ago in a shallow sea that extended over the southern part of North America. Mammoth Cave cuts through a total thickness of 300 ft of rock in the Girkin Formation, St. Genevieve Limestone, and the upper St. Louis Limestone (Palmer, 2002). A stratigraphic column showing the rock formations in which the Flint Mammoth Cave System is located can be seen in Figure 2 below.

Starting at the bottom of the section and moving up the stratigraphic column, the age of the rocks decreases. The lowest and oldest rock formation exposed in Mammoth Cave National Park is the St. Louis Limestone. While the entire St. Louis Limestone is more than 200 ft thick, only the top half can be seen in the cave. It can be identified by "the many beds and flat nodules of chert that stick out from the cave walls as black ledges and fins, or form irregular, resistant passage floors" (Palmer, 2002). These features can be seen below in Figure 3. Gypsum has also been found within the strata of the St. Louis Limestone in areas outside the cave, but near the caves, all these gypsum layers have been dissolved away by groundwater (Palmer, 2002).

The next rock formation moving up the stratigraphic column is the St. Genevieve Limestone, see Figure 4. This rock formation is approximately 110-120 ft thick and contains more cave passages than any other unit in the system. The St. Genevieve Limestone is composed predominantly of light gray limestone and dolomite (Palmer, 2002). The light gray limestone rocks "…alternate with thin beds of dark, silty, granular limestone…" (Palmer, 2002) in the upper half of the St. Genevieve. These impurities within the limestone are less resistant than the pure limestone and "weather inward as prominent niches in the cave walls (Palmer, 2002). The Ste. Genevieve does not contain gypsum.

The oldest caves in Mammoth Cave National Park are formed in the Girkin Formation. This formation is approximately 140 ft thick and is the youngest of the cave forming limestones in the park. The Girkin Formation "consists of light-gray limestone with minor dolomite, separated at intervals of roughly 20 ft by irregular beds of weak crumbly, shaly or silty limestone generally less than 3 ft thick that weather inward as recessed niches" (Palmer, 2002).

At the top of the stratigraphic column is the Big Clifty Sandstone. This formation is more resistant to weathering than the limestone beneath it. Because of this, the Big Clifty acts a cap rock diminishing the erosion of the limestone below. Because of its resistance to weathering, it forms the ridges within Mammoth Cave National Park. The Big Clifty ranges in thickness from 50-100 ft (Palmer, 2002).

2.2 Cave Geology

A landscape formed in limestone that consists of fissures, rock pinnacles, sinking streams, and closed depressions called sinkholes is called karst (Palmer, 2007). The Mammoth Cave region of central Kentucky is dominated by karst features. The caves of the Park were formed by solution of the limestone bedrock by water that seeped through small cracks and pores in the rocks. Over time the original openings enlarge to form caves and caverns.

The area to the southeast of Mammoth Cave National Park is called the Pennyroyal Plateau (Palmer, 2002). This area is a sinkhole plain, a broad, low relief plateau that contains extensive arrays of sinkholes. Here, all of the Big Clifty Formation has eroded away exposing the Girkin Formation at the surface. Figure 5 is a cross section of the Mammoth Cave Region.

Mammoth Cave National Park lies in the area known as the Chester Upland. In this area, the Big Clifty Formation is not completely eroded away. It forms the ridges near the cave entrances (Palmer, 2002). Figure 6 shows the major caves of the Park and how they relate to the rocks exposed at the surface. This figure shows how the flow of water on the surface controls the caves below.

Rain water that falls in the Pennyroyal Plateau flows to and collects in the sinkholes where it is fed to underground cave streams. Most of the rain that falls in the Chester Upland does not permeate the sandstone. Instead, it drains off the ridges and is channeled into the sinkholes at the margin of the upland. For this reason, the largest sinkholes occur at the contact between the Big Clifty Formation and the Girkin Formation. The sinkhole plain is the primary recharge area of the groundwater system (Palmer, 2002).

To the northwest of Mammoth Cave lies the Green River. It is the discharge area for the water passing through the cave system. The rise and fall of the river over millions of years has resulted in the different levels of passages in Mammoth Cave (Palmer, 2002).

All the rock formations in this part of central Kentucky are tilted gently to the northwest. Because caves tend to form along the bedding planes, it is this tilt that has caused the caves to generally trend to the northwest.

2.3 Small-Scale Cave Features

Moving water not only affects the formation of the cave passage, but also small-scale features that can cover the walls, ceiling and floor of the cave. Speleothems, commonly called cave formations, are secondary mineral deposits within caves. Speleogens are features caused by solution of the cave wall (Palmer, 2007).

There are many types of speleothems. They include flowstone, dripstone, stalactites, stalagmites and others. Some are common in Mammoth Cave. Flowstone, which consists of sheets composed primarily of calcite deposited where water runs down the walls, is an example of a speleothem common in Mammoth Cave (Palmer, 2007). The Frozen Niagara formation is a famous example of flowstone. This 75 ft formation is the centerpiece of the Frozen Niagara Tour. Stalactites and stalagmites are features that crystallize slowly over time from water that drips from the ceiling or deposits on the floor respectively (Palmer, 2007). While less common in Mammoth Cave, there are impressive examples near the Violet City entrance.

While Mammoth Cave may lack extensive speleothems, it has abundant solution features. There are many types of solution features including flutes, bell holes, solution notches and ceiling channels. Small, sinuous tunnels that interconnect in a braided, maze-like design are called anastomoses. They tend to form along bedding planes. If the lower bed falls, the upper bed shows the channels left in the ceiling (Palmer, 2007).

Examples of these features are prevalent in Mammoth Cave and can be seen in Figure 7. Another feature common in Mammoth Cave is scallops. Figure 8 shows examples of small-scale scallops. Scallops have many interesting properties that can be used to interpret the paleohydrologic characteristics of the cave.

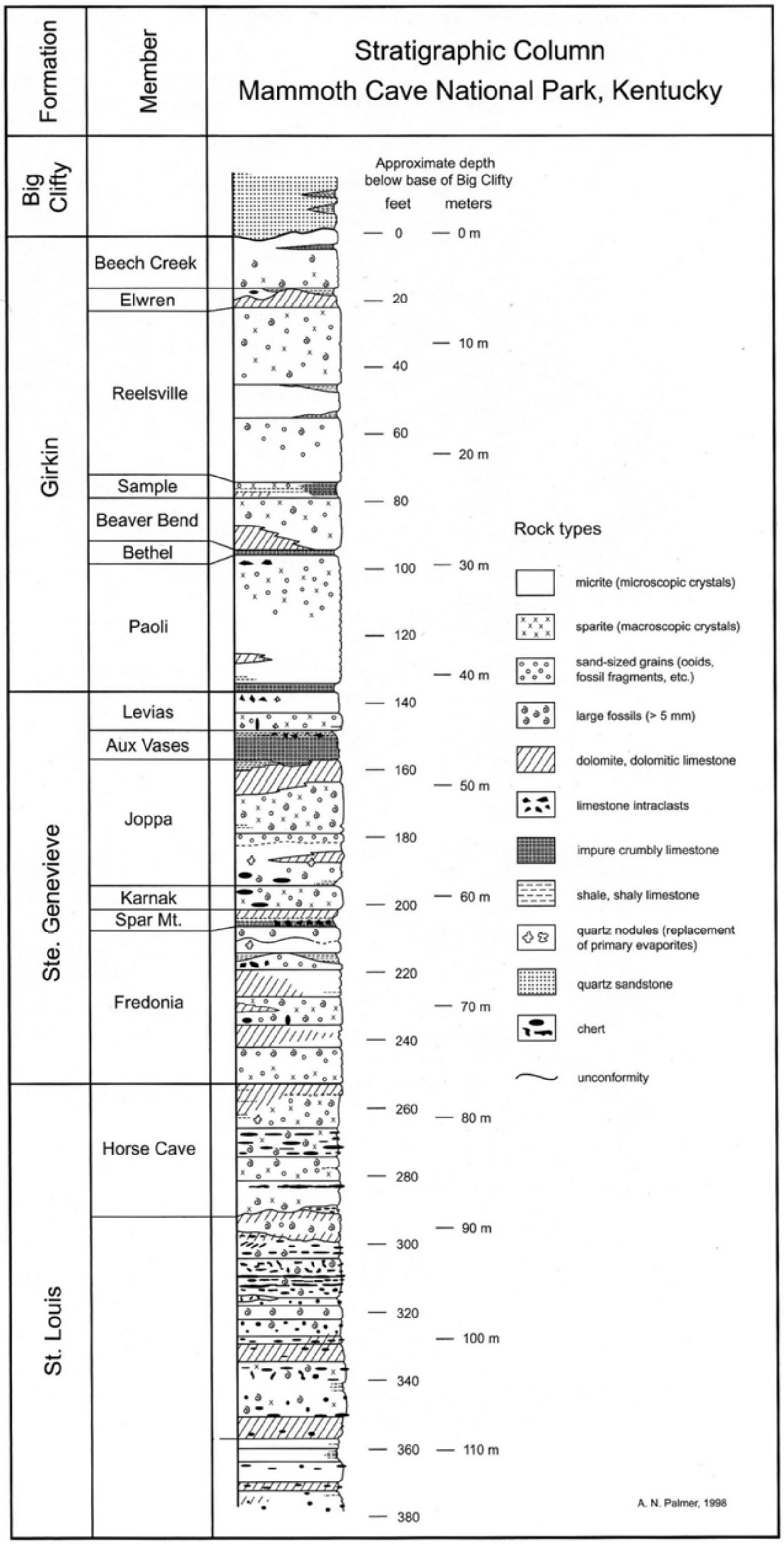

Figure 2. A stratigraphic column in the Mammoth Cave region, Kentucky (Palmer, 2007).

Figure 3. Chert nodules protruding from the limestone ceiling (Rader, 2008).

Figure 4. Typical passage wall in the St. Genevieve Limestone (Rader, 2008).

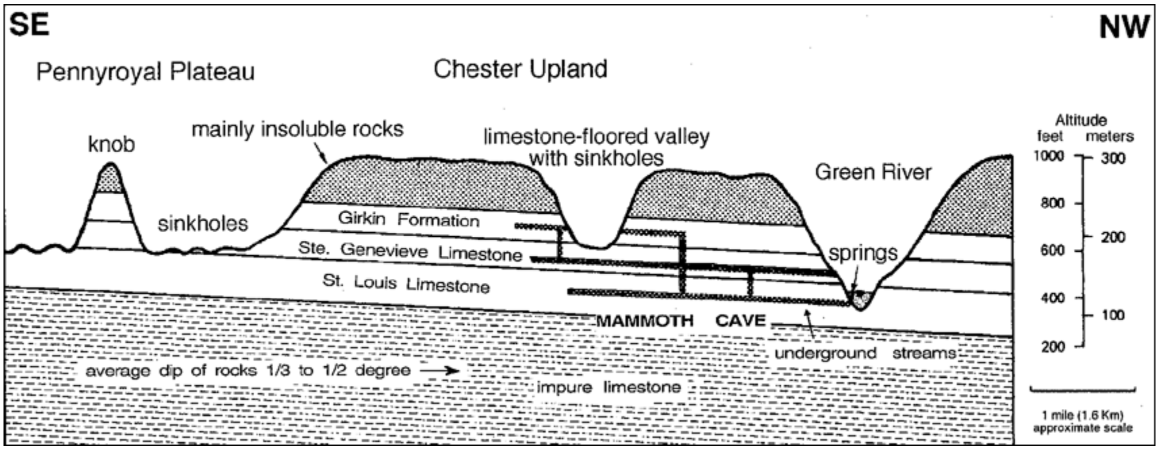

Figure 5. Cross Section of the Mammoth Cave Region (Palmer, 2004).

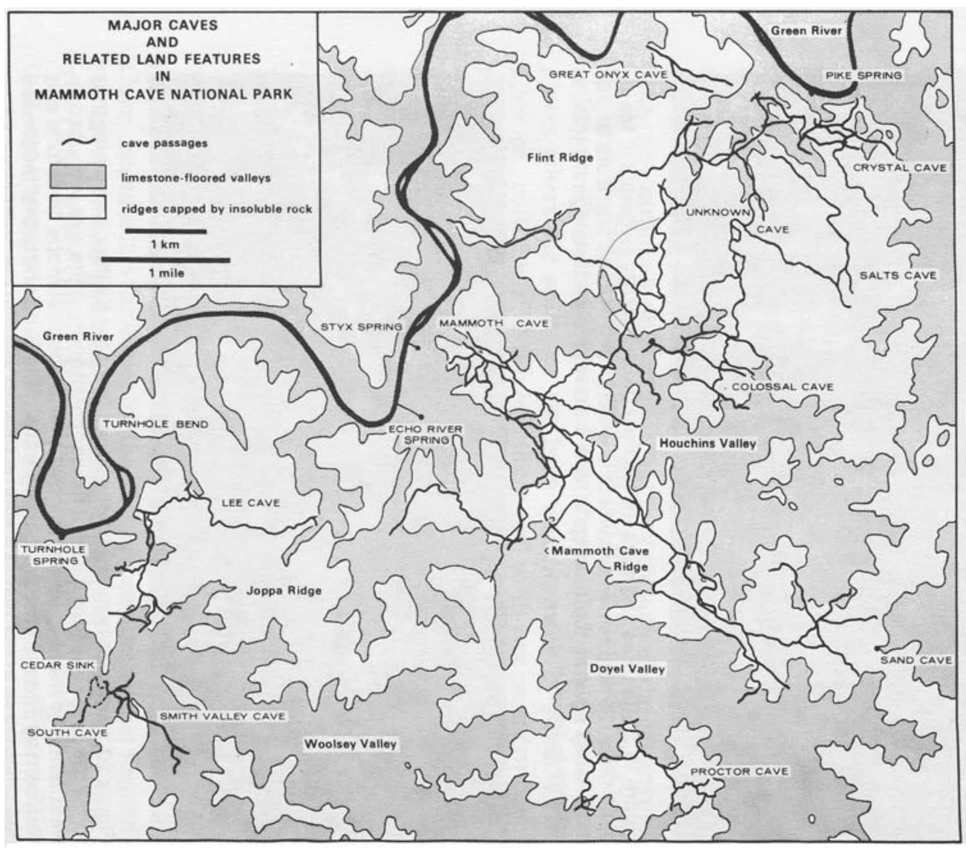

Figure 6. Map of Mammoth Cave Region showing major caves and their relation to land surface features (Palmer, 2004)

Figure 7. Anastomoses in the ceiling of a cave passage in the Ste. Genevieve Limestone (Rader, 2008).

Figure 8. Small scallops in the wall of a cave passage (Bair, 2008),

IIIA. Scallops

3A.1 Background

A scallop is an asymmetrical concavity dissolved in the bedrock surface by turbulent water (Palmer, 2007). Many of the passages in Mammoth Cave are inscribed with them. An example of a scallop can be seen in Figure 9. They range in length from about half a centimeter to one or two meters. The asymmetrical nature of scallops provides important information about the direction of water flow. The shallow side of the depression points downstream (Palmer, 2007). A scallop is shaped somewhat like a spoon. Using this analogy, the handle of the spoon points upstream. This can be seen it the diagram in Figure 10.

Scallops can be used to determine the velocity of water that formed them. Scallops depict peak flow rates of the water that most recently expanded the passage in which they are present. The length of a scallop must be measured to estimate the velocity of water that made it. Figure 10 shows a cross-sectional view of several scallops and indicates their length and the flow direction. In general, the smaller the scallop the faster the water was flowing. A simplified approximation of water velocity can be calculated by measuring the scallop length in centimeters, and dividing by 350. This yields rough approximations in centimeters per second of the velocity of water flowing past the walls of the cave passage (Palmer, 2007; Curl, 1974). A more precise calculation can also be used and is demonstrated below.

3A.2 Methods of Study

To acquire accurate water velocities, careful scallop measurements must first be taken. A carpenter's tool is used to produce the true shape of the scallop. The tool has small pins aligned in a plane that move independently of each other. Using this tool, the shape of the scallop can easily be seen and measured. The following procedure can be seen in Figure 9. The tool is pressed into the scallop, forcing the pins into the shape of the scallop. From the tool, a measurement can easily be taken. All scallop measurements are taken in inches and converted to centimeters.

The method for determining flow velocity from scallop length was established by Curl (1966, 1974) and Blumberg and Curl (1974). To simplify the process, a graph has been constructed from the equations. Curl's graph can be seen in Figure 11 (Palmer, 2007).

Curl (1974) recommends measuring all the scallops and using a weighted mean that favors the larger ones. Using this method ensures that the cave was probably completely full of water at the time the scallops were formed (Palmer, 2007).

The velocity of the water increases away from the cave walls as seen in Figure 12. Because of this, the size and shape of the passage must also be accounted for when determining peak flow velocity. If the passage is roughly circular, the graph can be used. Each of the four bold lines on the graph represent an approximate diameter, 0.5, 1, 2, 5 , and 10 m (Palmer, 2007). The graph can also account for vadose passages, represented by the dashed lines.

Water temperature can also play a role in determining peak flow velocity. As temperature increases, the velocity computed for a certain scallop length decreases. Water temperature for a now dry passage may be hard to determine. Any sediments that might indicate environmental conditions can be used. For example, if glacial sediment is present in the passage, it is fair to assume that the water forming the passage is glacial meltwater and that it is between 0 and 3°C. Current water temperatures in an active passage might also be used to determine past conditions (Palmer, 2007).

Once a mean scallop length is calculated and passage size, shape, and water temperature are accounted for, the graph can be read.

Figure 9. Picture shows a scallop and the carpenter's tool used to measure it (Bair, 2007).

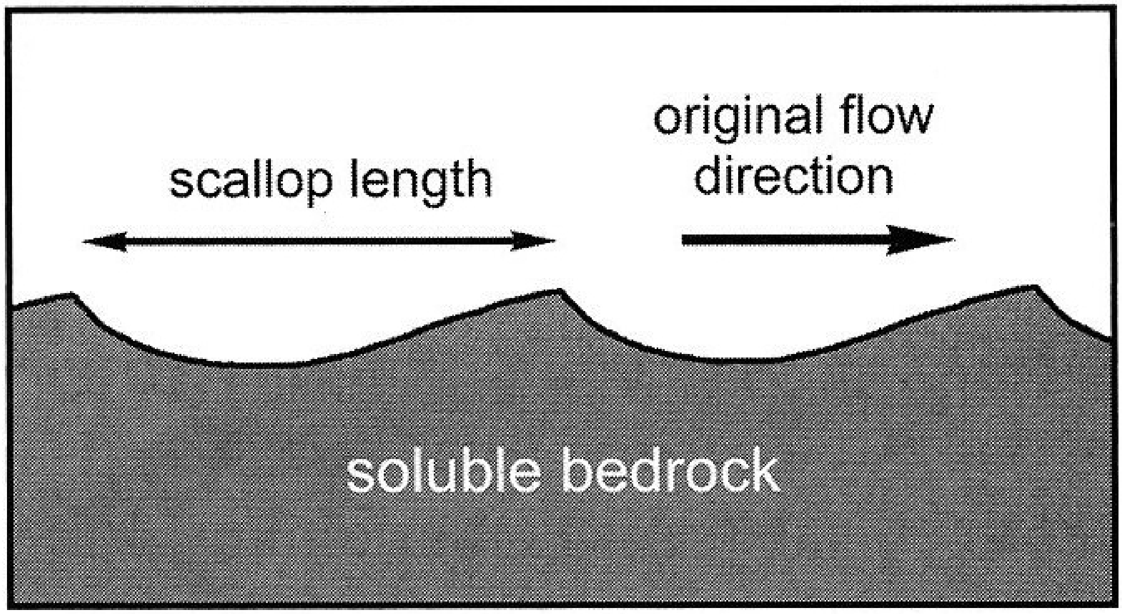

Figure 10. Cross section view of a scallop showing shape and direction of flow (Palmer, 2007).

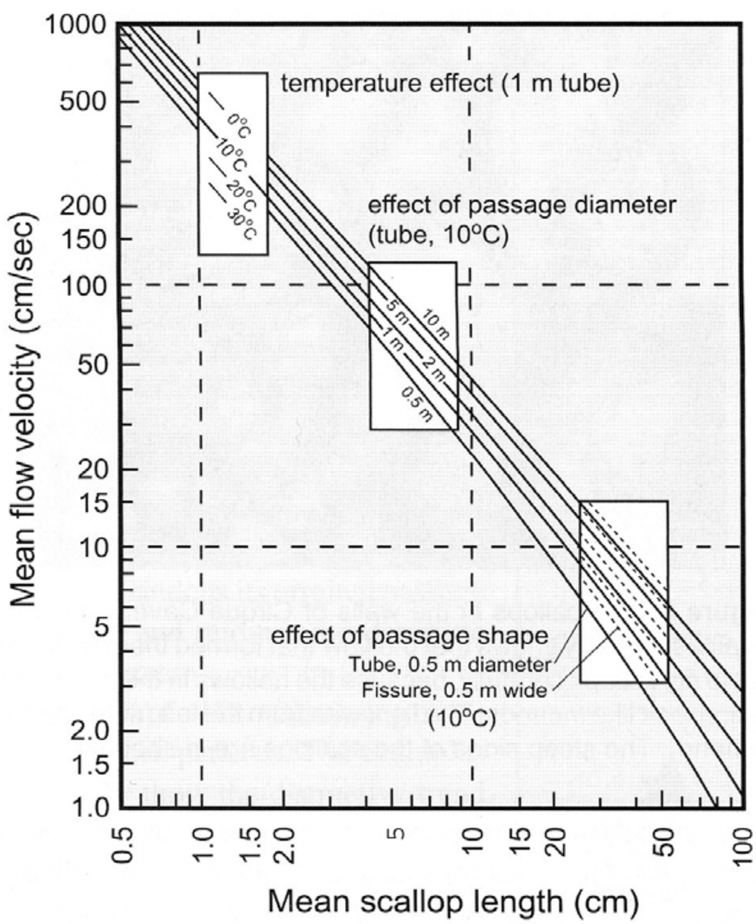

Figure 11. Curl's graph for estimating peak flow velocity from mean scallop length (Palmer, 2007).

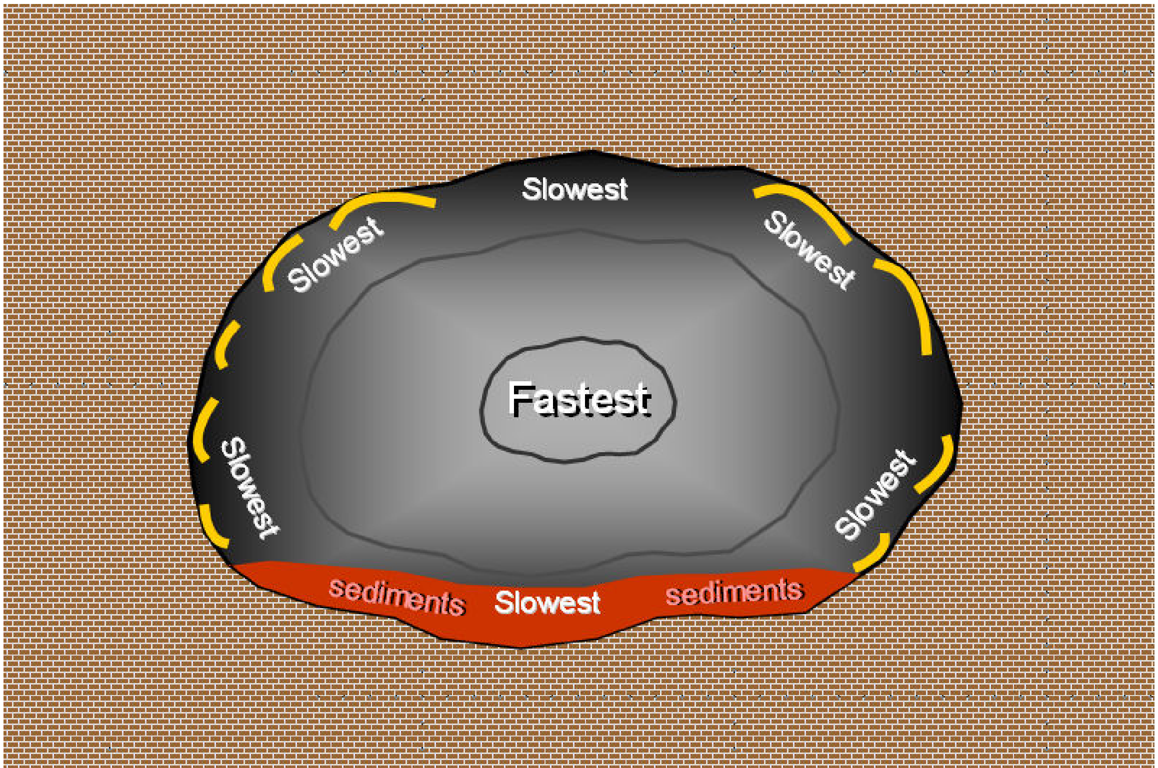

Figure 12. Diagram showing relative water velocities in a phreatic passage (Bair, 2008).

3A.3 Data and Analysis

All scallop length measurement data can be seen in Appendix A. Scallop measurements are divided into sections based on which passage they are located and then by their height above the floor. Measurements were taken from the following passages: Audubon Ave, Fat Man's Misery, River Hall, Jeanne's Ave and two locations on Kentucky Ave. The locations of the research areas can be seen in Appendix C. Statistical data, including median, mean, maximum, minimum, standard deviation and number of measurements taken, is then computed for each of the passages. A grand total of each statistic was also computed for all scallop measurements together. Histograms have been created to show any skew of the data. Select histograms can be seen in Figure

13, Figure 14, and Figure 15.

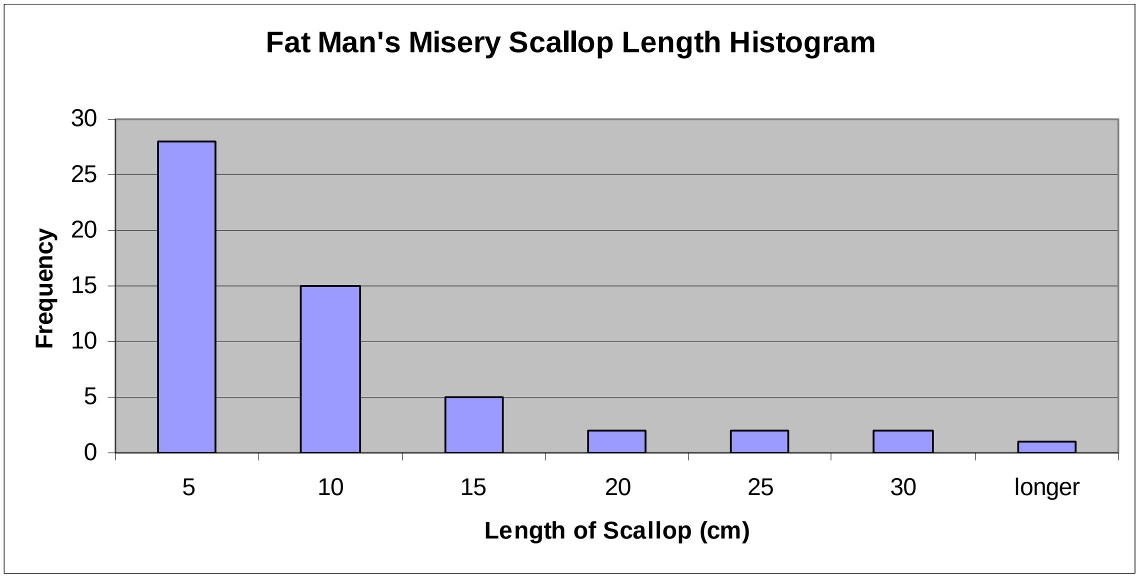

Figure 13.

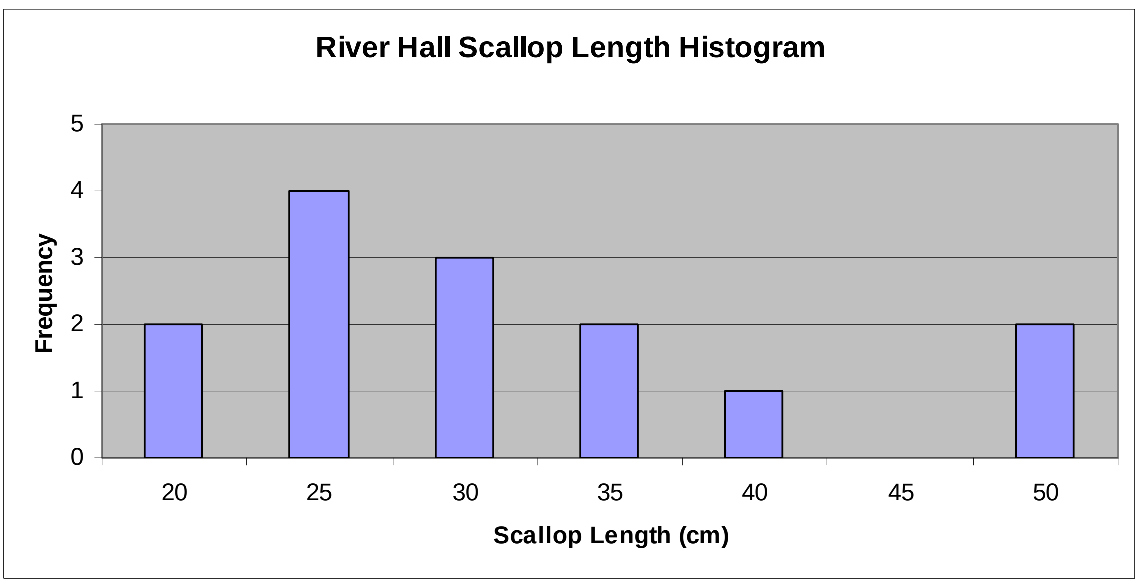

Figure 14.

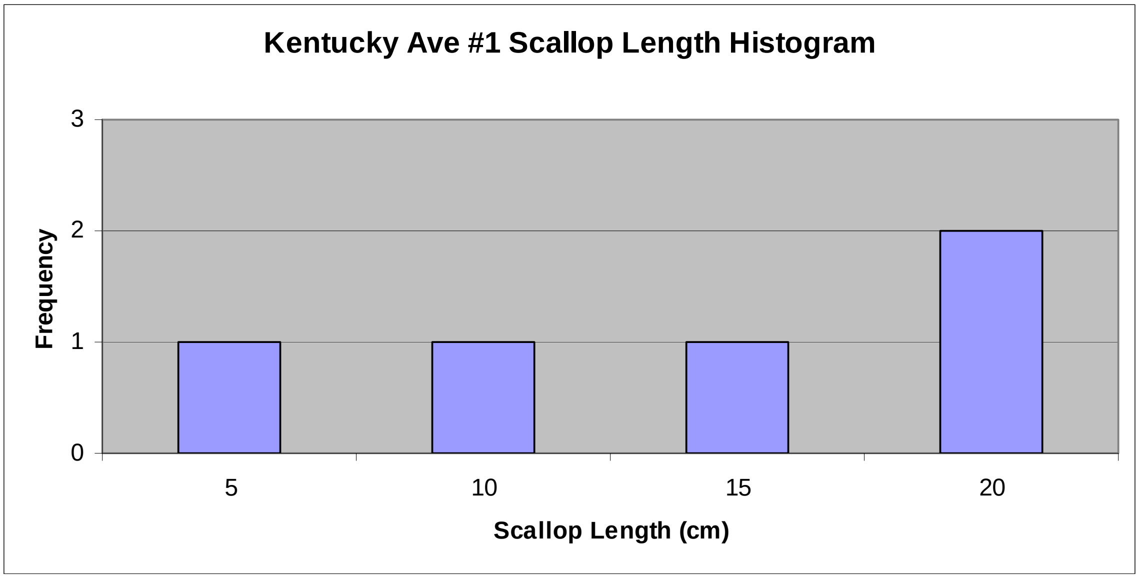
Kentucky Ave #1 Scallop Length Histogram
Frequency
3
2
1
0
5
10
15
20
Scallop Length (cm)

Figure 15.

IIIB. Passage Size

3B.1 Background

Cave passages can vary greatly in size and shape. Tubular passages are passages with an elliptical cross section (see Figure 16). Often called phreatic passages, they are formed at or below the water table. Because of this, they were nearly completely filled with water during their development. They enlarge along their entire perimeter (Palmer, 2007).

Canyon passages are high, narrow and sinuous (see Figure 17). Called vadose passages, they form above the water table. Groundwater in vadose passages cuts down rapidly through the bedrock to reach the water table. These passages are often deflected laterally into a variety of levels due to separations in bedding planes. The width of a vadose passage is proportional to the discharge of the cave stream that forms it. Vadose passages often feed into phreatic passages (Palmer, 2007).

Some passages are a combination of passage types. For example, Fat Man's Misery originally formed as a phreatic passage. Later, it transitioned into a vadose passage, probably due to a drop in the level of the Green River. As the level of the Green River fell, the water running through the passage quickly cut down through the bottom of the tubular to create a canyon shaped passage. This type of passage is often called a keyhole passage due to its unique shape, which can be seen in Figure __.

The size and shape of the cave passage are an important factor when using the Curl (1974) graph to estimate flow velocities and, therefore, must be measured in the field.

3B.2 Methods of Study

To estimate the flow discharge of a passage, an accurate area must be measured, in addition to the scallop data. To do this several tools are needed. A laser distance meter is used to measure the distance to the ceiling and floor from an arbitrary datum. A level is used to ensure that the datum is horizontal. A measuring tape is to mark regular intervals along the datum. These points are where the distance meter measurements are taken. This process can be seen in Figure 19.

From these data, cross sections can be constructed. The x axis represents distance along the datum, with distances to the ceiling plotted as positive values (y1) and distance to the floor plotted as negative values (x2).

With these same measurements, the approximate area of the cave passage can also be calculated. The difference between the two y values is the height of the cave passage. The distance between interval readings is the width. The area is computed by multiplying the height and the width of each measured section along the datum and summing the areas of the sections.

Figure 16. Cleaveland Ave, an example of a phreatic passage, showing elliptical shape (Peter, 2008).

Figure 17. Boone Ave, an example of vadose passage, showing high, narrow and sinuous shape (Bair, 2008).

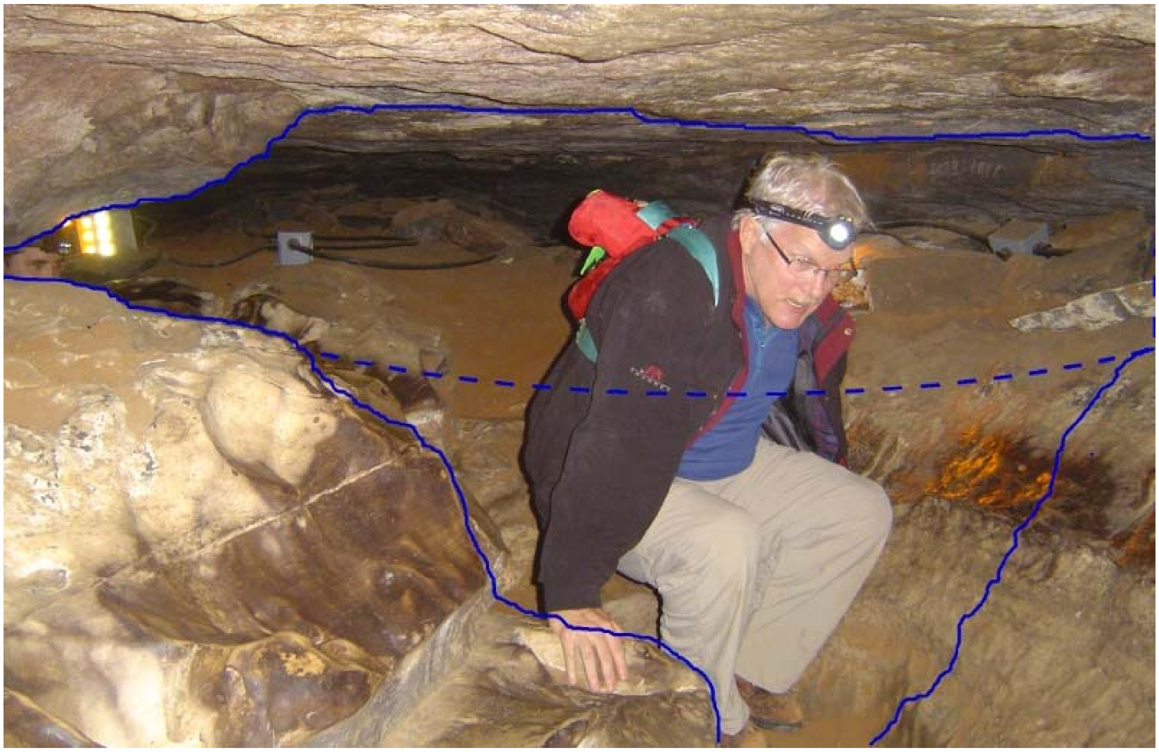

Figure 18. Fat Man's Misery, a keyhole passage: phreatic at the ceiling, vadose at the floor (Rader, 2008).

Figure 19. Shows the process of creating the cross section (Bair, 2008).

3B.3 Data and Analysis

Passage size measurements can be found in Appendix B. All measurements were taken in feet or converted to feet for the table. Eight passages were measured: Fat Man's Misery, Leopard Arch, River Hall, Jeanne's Ave, two from Cleaveland Ave and two from Kentucky Ave. Appendix C shows the location where the data was collected.

The first column in Appendix B is the x axis value or the datum. Y1 is the distance from the datum to the ceiling, and Y2 is the distance to the floor. All Y2 values are negative, meaning below the datum. Some passages have adjusted X values. This was done to shift the graph right or left to normalize the positions of the passages, which allows for easier comparison of passage size.

There are three other columns labeled width, height, and area in Appendix B. Width is the distance between measurements along the datum and is constant for each passage. Height was calculated as described above. Width and height were then multiplied to obtain the area of the segment. The areas of each segment are then added together to estimate the total area of the passage.

These data points were then graphed to compare different passages. Examples of select passages can be seen in Figures 20, 21 and 22.

Kentucky Ave #1 and #2 Passage Size Comparison

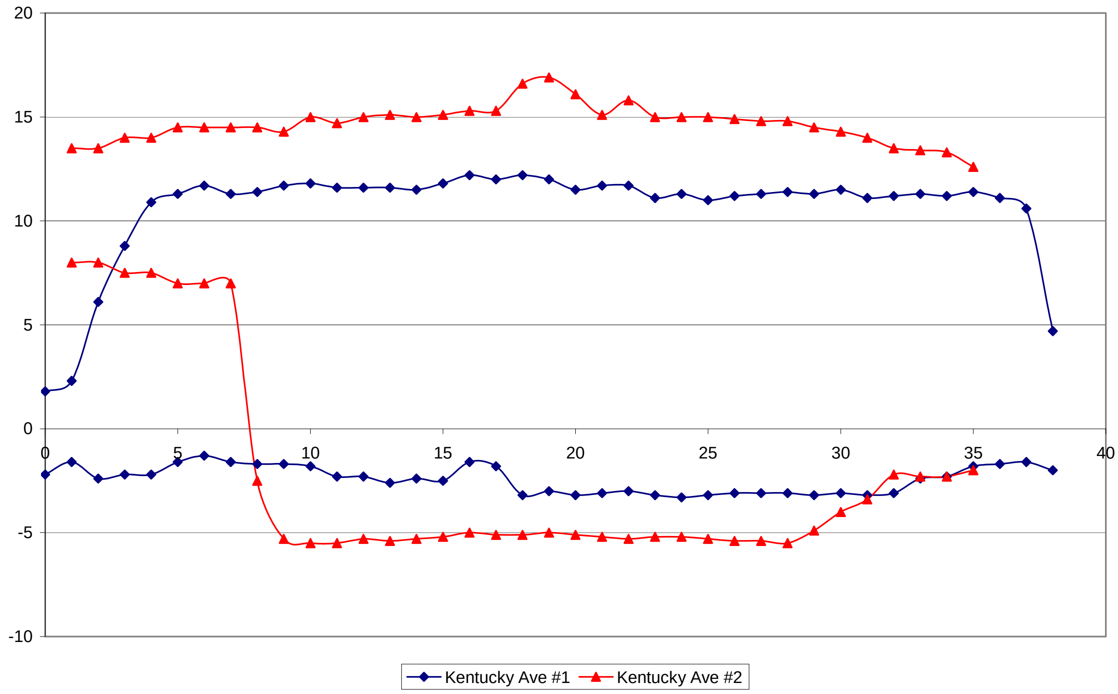

Figure 20.

Fat Man's Misery And Leopard Arch Passage Size Comparison

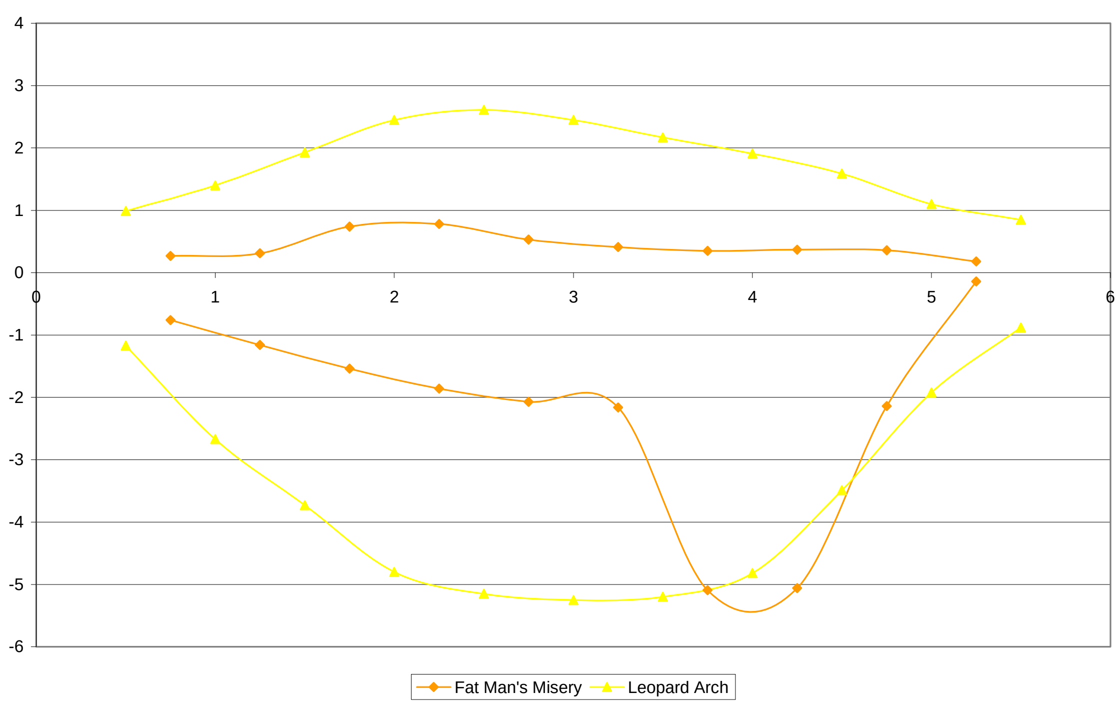

Figure 21.

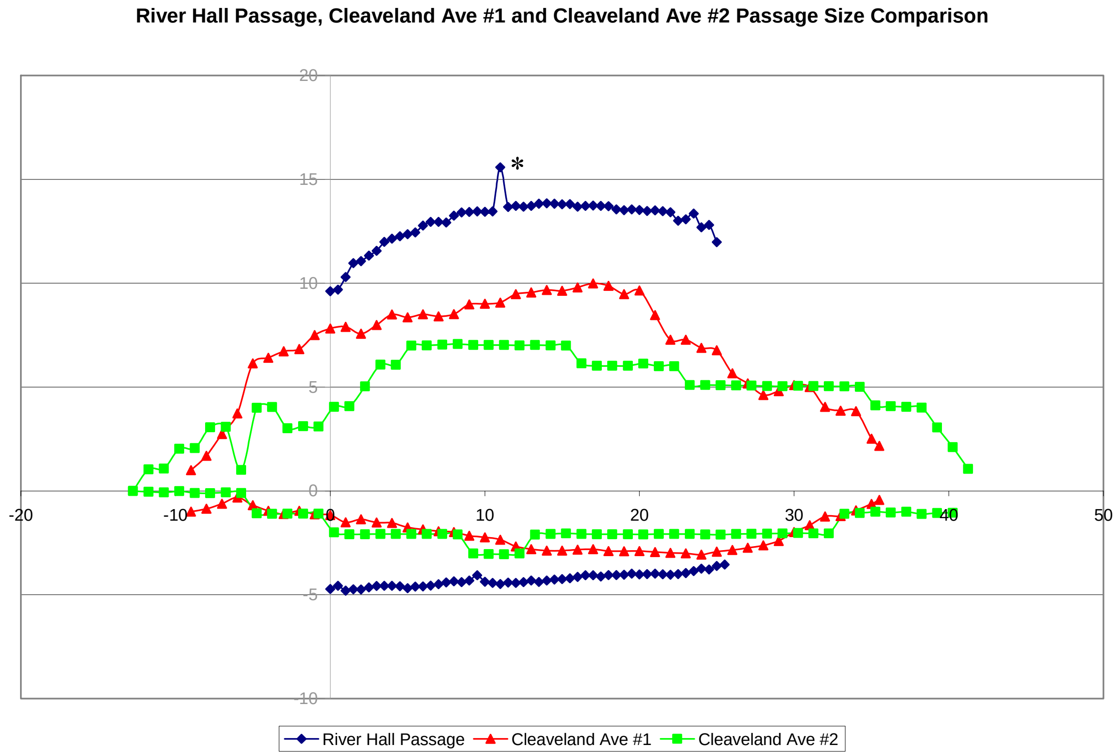

Figure 22. *Probable erroneous data point.

IIIC. Interpretations

Figure 23 is a table with all the research data displayed for comparison. From these data, several graphs have been constructed to help show the relationships between the parameters. For consistency, all legends are the same from graph to graph. Vadose passages are represented as squares ■, and phreatic passages as diamonds ◊. Fat Man's Misery is combination of both types: phreatic near the top and transitioning to vadose at the bottom is represented as a plus sign +.

Figure 24 is a graph of distance from the discharge area of the cave system to each measured passage. The passages have been divided based on the level of the cave in which they formed. Level I, the highest and oldest, is represented by Kentucky Ave #1, Kentucky Ave #2, and Jeanne's Ave, starting upstream and moving downstream. Level II, the next level down, is represented by Cleaveland Ave #1 and Cleaveland Ave #2. Trendlines have been plotted for Level I passages and Level II passages. Both trendlines suggest that passage area decreases towards the discharge area to the west along the ancestral Green River. This is similar to a distributary channel system. Just as a large surface river can form a delta near its mouth, a major cave passage may form similar features underground to distribute water during periods of extreme high flows.

With mean water velocity and passage area estimated, mean discharge can now be estimated. This is done by multiplying the passage area in feet squared by the mean water velocity in feet per second to give the mean discharge of the passage in feet cubed per second. Figure 25 shows a graph of distance from discharge area verses discharge. The cave level is also considered here. In Level I, Kentucky Ave #1 shows high velocity and large area, which may reflect sampling bias in the selection of scallops measured. Just downstream of the Jeanne's Ave branch off, Kentucky Ave is blocked by an ancient collapsed sinkhole. Before the collapse, Jeanne's Ave flowed into Kentucky Ave. After the collapse, water was diverted into Jeanne's Ave, reversing its flow. The data are consistent with that theory. Moving from Kentucky Ave #2 to Jeanne's Ave, the passage area decreases. To accommodate the same amount of water, the velocity must increase, which the data also show. Fat Man's Misery, Level IV, shows high velocity and small passage area, consist with a vadose passage. River Hall, Level V, is an isolated, seemingly anonymous data point. More data need to be collected at each cave level to make further, stronger interpretations.

Figure 26 shows the relationship between passage area and distance to the discharge area. With no trends clearly visible, this graph suggests that more data are needed. In addition, more data are needed along Kentucky Ave to confirm or refute possible sampling bias. Additional data are needed up and down gradient of Fat Man's Misery so comparisons can be made. Data should also be collected on Boone Ave downstream of Jeanne's Ave to confirm findings at Kentucky Ave #2 and Jeanne's Ave.

Passage Name	Mean Scallop Length (cm)	Passage Diameter of Equivalent Circle (ft)	Passage Diameter of Equivalent Circle (m)	Mean Water Velocity (cm/sec)	Mean Water Velocity (ft/sec)	Passage Area (ft^2)	Mean Discharge (ft^3/sec)	Distance from Discharge Area (ft)*
Audubon Ave	20.9							420
Fat Man's Misery	10.3	4.1	1.2	30.0	1.0	13.1	12.9	1300
River Hall	34.9	23.7	7.2	9.5	0.3	441.5	137.6	1100
Jeanne's Ave	32.5	24.0	7.3	9.0	0.3	450.9	133.1	12000
Kentucky Ave #1	10.4	25.4	7.8	39.0	1.3	507.9	649.7	15000
Kentucky Ave #2	72.1	27.4	8.4	3.9	0.1	590.3	75.5	14000
Cleaveland Ave #1		22.6	6.9			402.1		9600
Cleaveland Ave #2		21.0	6.4			345.4		7800
Leopard Arch		6.1	1.9			29.3		1000

Blank cells indicates data was not collected in that area.
*Historic Entrance used as estimate of the discharge area.

Figure 23. Table of data collected with appropriate conversions.

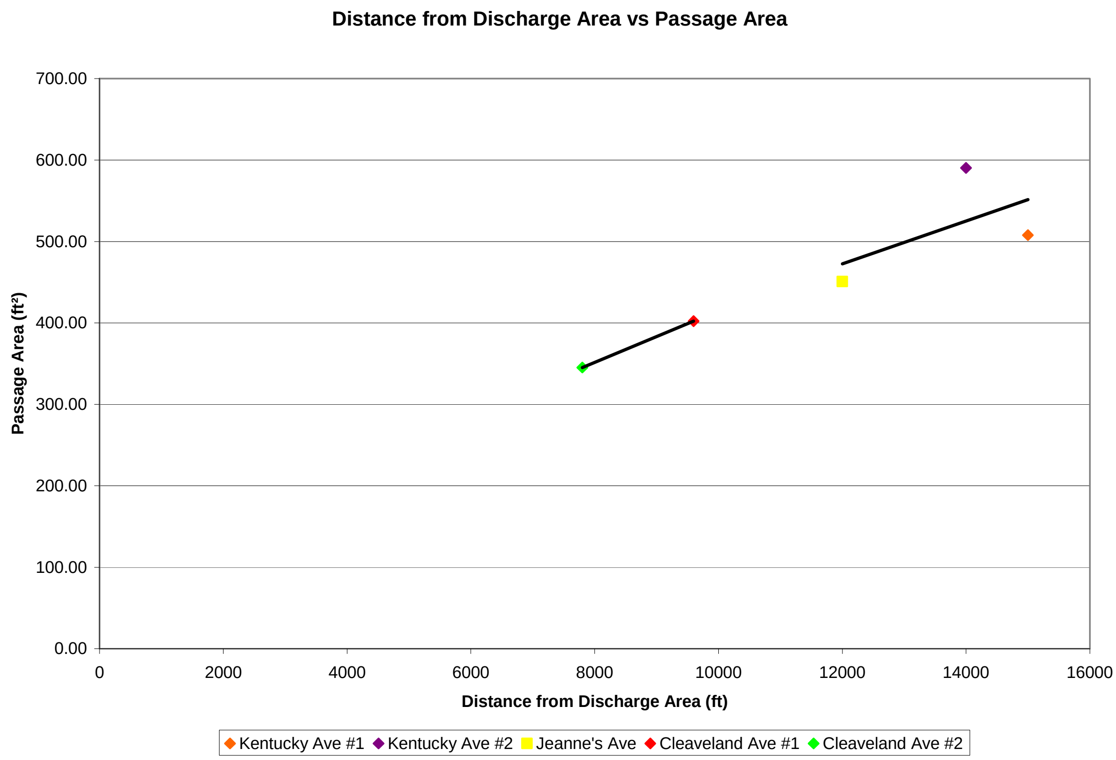

Figure 24.

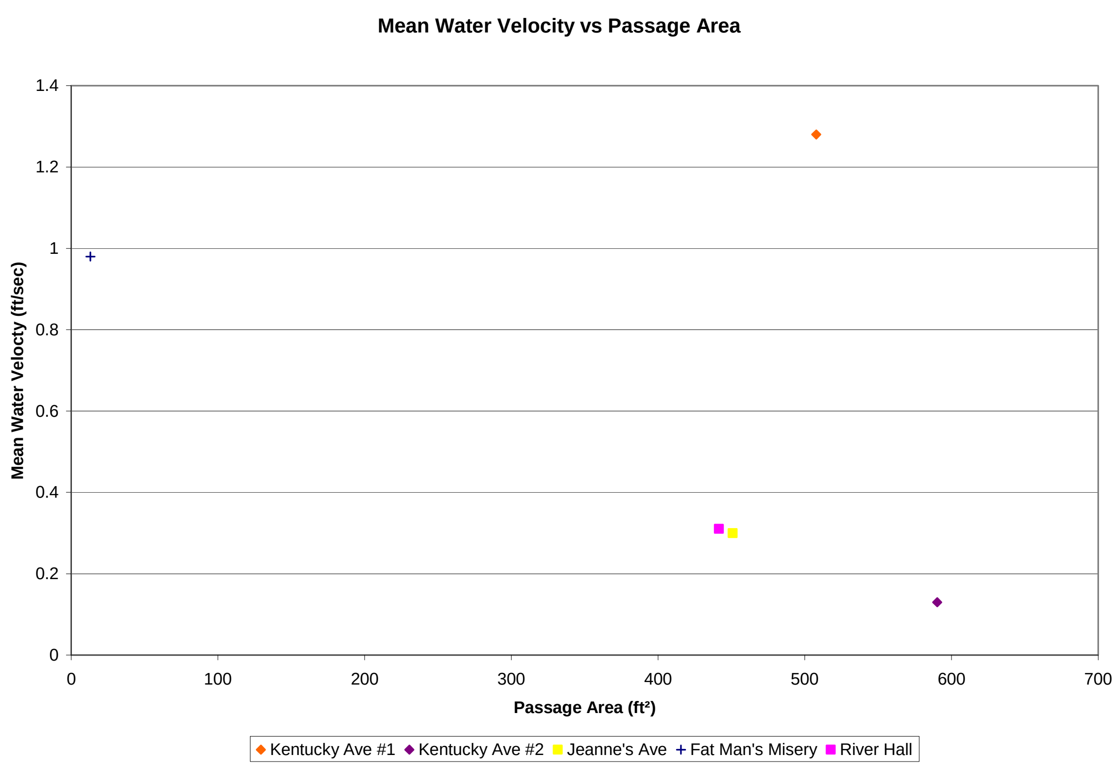

Figure 25.

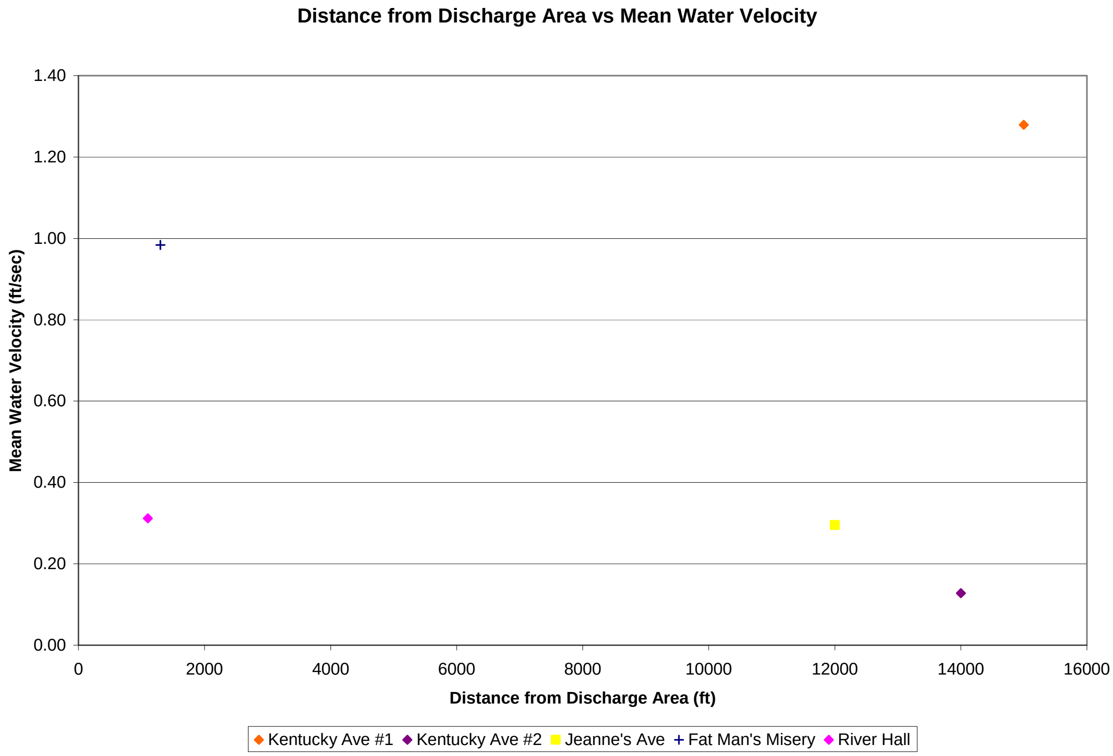
Distance from Discharge Area vs Mean Water Velocity
Mean Water Velocity (ft/sec)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
2000
4000
6000
8000
10000
12000
14000
16000
Distance from Discharge Area (ft)
Kentucky Ave #1
Kentucky Ave #2
Jeanne's Ave
Fat Man's Misery
River Hall

Figure 26.

IV. Summary and Conclusions

The purpose of this study was to estimate mean discharge of select passages in Mammoth Cave. Scallops were measured at six locations within Mammoth Cave. The scallop lengths were then averaged. Passage area was measured at eight locations. Curl's graph (1974) was used to estimate flow velocity of the water that most recently enlarged that passage. The value of velocity from the graph was then multiplied by the passage area to estimate mean flow discharge of the passage.

Data were plotted against distance from the discharge area. These graphs were analyzed for trends. Data from the distance to discharge area versus passage area graph suggests that during high flows, water in the cave streams is distributed to multiple streams similar to distributary delta channel system. The mean velocity versus passage area graph suggests an increase in water velocity due to a decrease in passage area.

Both scallop measurements and passage area were collected for only five passages. With these limited data sets, trends could not easily be identified. Sampling bias due to the lack of ability to collect scallop measurements from the entire height of the cave passage may have also influenced the results. Suggestions for further study have already been stated.

V. References

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VI. Appendixes

Appendix A: Scallop Length Measurements for Select Passages

All measurements in centimeters unless otherwise noted.

Audubon Avenue	62.5		
	8		
	24		
	19		
	17.5	Median	17.5
	20	Average:	20.86363
	13	Max:	62.5
	21	Min:	8
	14	stdev:	14.48290
	16	Number	11
	14.5		
Fat Man's Misery	4		
head height	10		
	8		
	8		
	26		
	13.5		
	6		
	5		
	30		
	25		
	15		
	25		
	2		
	2.5		
	11		
	7		
	4		
	7		
	20		
	40		
knee height	6		
	7		
	5		
	3		
	4		
	4		
	6		
	4		
	6		
	3.5		
	2		
	2		
	5		
	3		

	5.5		
	5		
	6.5		
	3		
	3.5		
	4.5		
	3		
	4.5		
	2.5		
	2		
	10.5		
	3		
	12		
	2.5		
	3	Median	6
	20	Average:	10.25303
	5.5	Max:	62.5
	9	Min:	1.2
	5	stdev:	10.41815
ankle height	1.2	Number	66
	6		
River Hall	55		
	40		
	23		
	30		
	31		
	30		
	38		
	52	Median	32
	34	Average:	34.89285
	22.5	Max:	55
	30	Min:	22.5
	33	stdev:	9.571951
	29	Number	14
	41		
Jeanne's Ave	34		
head height	6		
	74		
	50		
	55		
	42		
	42		
	52		
	21		
	46		
	34		
	30		
	45		
	32		
	25		
	37		
	62		
	34	Median	34

	19	Average:	32.45833
	20	Max:	74
ankle height	4	Min:	3
	6	stdev:	19.39739
	3	Number	24
waist height	6		
Kentucky Ave #1		Median	10.16
chest height	2.23	Average:	10.352
	5.08	Max:	17.78
	10.16	Min:	2.23
	17.78	stdev:	6.835456
	16.51	Number	5
Kentucky Ave #2	106.68		
~15 ft	137.16		
	48.25		
	50.81	Median	66.05
	45.72	Average:	72.137
	45.72	Max:	137.16
	66.05	Min:	45.72
	71.11	stdev:	29.91470
	66.05	Number	10
	83.82		
Grand Totals			
Median	15		
Average:	22.83470		
Max:	137.16		
Min:	1.2		
stdev:	23.45807		
Number	119		

Appendix B: Passage Size Measurements for Select Passages

All measurements are given in feet.

Fat Man's Misery

X	Y1	Y2	X adjusted	Width	Height	Area
3	0.27	-0.76	0.75	0.5	1.03	0.515
3.5	0.31	-1.16	1.25	0.5	1.47	0.735
4	0.74	-1.54	1.75	0.5	2.28	1.14
4.5	0.78	-1.86	2.25	0.5	2.64	1.32
5	0.53	-2.07	2.75	0.5	2.6	1.3
5.5	0.41	-2.16	3.25	0.5	2.57	1.285
6	0.35	-5.09	3.75	0.5	5.44	2.72
6.5	0.37	-5.06	4.25	0.5	5.43	2.715
7	0.36	-2.14	4.75	0.5	2.5	1.25
7.5	0.18	-0.14	5.25	0.5	0.32	0.16
				Total Area		13.14

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Leopard Arch

X	Y1	Y2	X adjusted	Width	Height	Area
0.5	0.99	-1.17	-2.25	0.5	2.16	1.08
1	1.4	-2.67	-1.75	0.5	4.07	2.035
1.5	1.93	-3.73	-1.25	0.5	5.66	2.83
2	2.45	-4.8	-0.75	0.5	7.25	3.625
2.5	2.61	-5.15	-0.25	0.5	7.76	3.88
3	2.45	-5.25	0.25	0.5	7.7	3.85
3.5	2.17	-5.2	0.75	0.5	7.37	3.685
4	1.91	-4.82	1.25	0.5	6.73	3.365
4.5	1.59	-3.49	1.75	0.5	5.08	2.54
5	1.1	-1.92	2.25	0.5	3.02	1.51
5.5	0.85	-0.88	2.75	0.5	1.73	0.865
				Total Area		29.265

River Hall Passage

X	Y1	Y2	Width	Height	Area
0	9.61	-4.72	0.5	14.33	7.165
0.5	9.69	-4.57	0.5	14.26	7.13
1	10.3	-4.8	0.5	15.1	7.55
1.5	10.97	-4.73	0.5	15.7	7.85
2	11.06	-4.74	0.5	15.8	7.9
2.5	11.33	-4.65	0.5	15.98	7.99
3	11.56	-4.58	0.5	16.14	8.07
3.5	11.99	-4.57	0.5	16.56	8.28
4	12.14	-4.57	0.5	16.71	8.355
4.5	12.26	-4.59	0.5	16.85	8.425
5	12.36	-4.69	0.5	17.05	8.525
5.5	12.45	-4.61	0.5	17.06	8.53

6	12.78	-4.6	0.5	17.38	8.69		
6.5	12.95	-4.56	0.5	17.51	8.755		
7	12.95	-4.49	0.5	17.44	8.72		
7.5	12.92	-4.4	0.5	17.32	8.66		
8	13.25	-4.35	0.5	17.6	8.8		
8.5	13.41	-4.39	0.5	17.8	8.9		
9	13.43	-4.32	0.5	17.75	8.875		
9.5	13.46	-4.06	0.5	17.52	8.76		
10	13.44	-4.37	0.5	17.81	8.905		
10.5	13.46	-4.43	0.5	17.89	8.945		
11	15.58	-4.48	0.5	20.06	10.03		
11.5	13.67	-4.41	0.5	18.08	9.04		
12	13.72	-4.43	0.5	18.15	9.075		
12.5	13.68	-4.39	0.5	18.07	9.035		
13	13.72	-4.32	0.5	18.04	9.02		
13.5	13.83	-4.38	0.5	18.21	9.105		
14	13.85	-4.32	0.5	18.17	9.085		
14.5	13.83	-4.27	0.5	18.1	9.05		
15	13.8	-4.25	0.5	18.05	9.025		
15.5	13.81	-4.21	0.5	18.02	9.01		
16	13.68	-4.14	0.5	17.82	8.91		
16.5	13.72	-4.06	0.5	17.78	8.89		
17	13.74	-4.06	0.5	17.8	8.9		
17.5	13.72	-4.12	0.5	17.84	8.92		
18	13.71	-4.05	0.5	17.76	8.88		
18.5	13.56	-4.05	0.5	17.61	8.805		
19	13.52	-4.03	0.5	17.55	8.775		
19.5	13.56	-3.98	0.5	17.54	8.77		
20	13.53	-4.02	0.5	17.55	8.775		
20.5	13.48	-4	0.5	17.48	8.74		
21	13.51	-3.98	0.5	17.49	8.745		
21.5	13.47	-4.01	0.5	17.48	8.74		
22	13.42	-4.03	0.5	17.45	8.725		
22.5	13.01	-4	0.5	17.01	8.505		
23	13.08	-3.96	0.5	17.04	8.52		
23.5	13.35	-3.86	0.5	17.21	8.605		
24	12.69	-3.74	0.5	16.43	8.215		
24.5	12.81	-3.78	0.5	16.59	8.295		
25	11.98	-3.61	0.5	15.59	7.795		
25.5		-3.55	0.5	3.55	1.775		
			Total Area		441.54		
Cleaveland Ave #1							
			X adjusted		Width	Height	Area
1	1	-1	-9		1	2	2
2	1.69	-0.86	-8		1	2.55	2.55
3	2.74	-0.62	-7		1	3.36	3.36
4	3.73	-0.31	-6		1	4.04	4.04
5	6.14	-0.68	-5		1	6.82	6.82
6	6.41	-0.96	-4		1	7.37	7.37
7	6.72	-1.11	-3		1	7.83	7.83
8	6.83	-0.96	-2		1	7.79	7.79

9	7.5	-1.12	-1	1	8.62	8.62
10	7.82	-1.16	0	1	8.98	8.98
11	7.9	-1.51	1	1	9.41	9.41
12	7.57	-1.37	2	1	8.94	8.94
13	7.99	-1.52	3	1	9.51	9.51
14	8.49	-1.54	4	1	10.03	10.03
15	8.36	-1.76	5	1	10.12	10.12
16	8.5	-1.85	6	1	10.35	10.35
17	8.41	-1.94	7	1	10.35	10.35
18	8.51	-1.98	8	1	10.49	10.49
19	8.98	-2.15	9	1	11.13	11.13
20	9.01	-2.23	10	1	11.24	11.24
21	9.07	-2.35	11	1	11.42	11.42
22	9.48	-2.67	12	1	12.15	12.15
23	9.56	-2.81	13	1	12.37	12.37
24	9.67	-2.87	14	1	12.54	12.54
25	9.63	-2.87	15	1	12.5	12.5
26	9.8	-2.83	16	1	12.63	12.63
27	9.99	-2.81	17	1	12.8	12.8
28	9.88	-2.89	18	1	12.77	12.77
29	9.48	-2.9	19	1	12.38	12.38
30	9.65	-2.89	20	1	12.54	12.54
31	8.47	-2.94	21	1	11.41	11.41
32	7.28	-2.98	22	1	10.26	10.26
33	7.28	-3	23	1	10.28	10.28
34	6.89	-3.07	24	1	9.96	9.96
35	6.77	-2.92	25	1	9.69	9.69
36	5.66	-2.85	26	1	8.51	8.51
37	5.18	-2.74	27	1	7.92	7.92
38	4.62	-2.62	28	1	7.24	7.24
39	4.81	-2.41	29	1	7.22	7.22
40	5.1	-1.98	30	1	7.08	7.08
41	5	-1.65	31	1	6.65	6.65
42	4.05	-1.23	32	1	5.28	5.28
43	3.86	-1.21	33	1	5.07	5.07
44	3.84	-0.94	34	1	4.78	4.78
45	2.52	-0.63	35	1	3.15	3.15
45.5	2.17	-0.43	35.5	1	2.6	2.6
				Total Area		402.13
Cleaveland Ave #2						
				Width	Height	Area
0	0	0	-12.75	1	0	0
1	1.04	-0.04	-11.75	1	1.08	1.08
2	1.08	-0.07	-10.75	1	1.15	1.15
3	2.03	-0.01	-9.75	1	2.04	2.04
4	2.06	-0.1	-8.75	1	2.16	2.16
5	3.06	-0.11	-7.75	1	3.17	3.17
6	3.08	-0.07	-6.75	1	3.15	3.15
7	1.01	-0.1	-5.75	1	1.11	1.11
8	4	-1.08	-4.75	1	5.08	5.08
9	4.04	-1.1	-3.75	1	5.14	5.14
10	3.01	-1.09	-2.75	1	4.1	4.1
11	3.11	-1.09	-1.75	1	4.2	4.2

12	3.1	-1.09	-0.75	1	4.19	4.19
13	4.05	-2	0.25	1	6.05	6.05
14	4.08	-2.09	1.25	1	6.17	6.17
15	5.03	-2.09	2.25	1	7.12	7.12
16	6.08	-2.08	3.25	1	8.16	8.16
17	6.07	-2.08	4.25	1	8.15	8.15
18	7	-2.08	5.25	1	9.08	9.08
19	7.01	-2.08	6.25	1	9.09	9.09
20	7.04	-2.08	7.25	1	9.12	9.12
21	7.07	-2.1	8.25	1	9.17	9.17
22	7.02	-3.01	9.25	1	10.03	10.03
23	7.02	-3.04	10.25	1	10.06	10.06
24	7.02	-3.05	11.25	1	10.07	10.07
25	7.01	-3.01	12.25	1	10.02	10.02
26	7.02	-2.11	13.25	1	9.13	9.13
27	7.01	-2.08	14.25	1	9.09	9.09
28	7	-2.05	15.25	1	9.05	9.05
29	6.14	-2.08	16.25	1	8.22	8.22
30	6.02	-2.09	17.25	1	8.11	8.11
31	6.02	-2.09	18.25	1	8.11	8.11
32	6.02	-2.09	19.25	1	8.11	8.11
33	6.13	-2.1	20.25	1	8.23	8.23
34	6	-2.08	21.25	1	8.08	8.08
35	6	-2.08	22.25	1	8.08	8.08
36	5.1	-2.08	23.25	1	7.18	7.18
37	5.1	-2.1	24.25	1	7.2	7.2
38	5.09	-2.11	25.25	1	7.2	7.2
39	5.08	-2.08	26.25	1	7.16	7.16
40	5.07	-2.07	27.25	1	7.14	7.14
41	5.05	-2.06	28.25	1	7.11	7.11
42	5.04	-2.05	29.25	1	7.09	7.09
43	5.06	-2.03	30.25	1	7.09	7.09
44	5.05	-2.05	31.25	1	7.1	7.1
45	5.04	-2.05	32.25	1	7.09	7.09
46	5.03	-1.1	33.25	1	6.13	6.13
47	5.01	-1.06	34.25	1	6.07	6.07
48	4.11	-1.01	35.25	1	5.12	5.12
49	4.08	-1.04	36.25	1	5.12	5.12
50	4.05	-1.01	37.25	1	5.06	5.06
51	4.01	-1.11	38.25	1	5.12	5.12
52	3.05	-1.06	39.25	1	4.11	4.11
53	2.11	-1.05	40.25	1	3.16	3.16
54	1.06		41.25	1	1.06	1.06
				Total Area		345.38

Jeanne's Ave

X	Y1	Y2	Width	Height	Area
0	22.09	0	1	22.09	22.09
1	22.14	-3.83	1	25.97	25.97
2	21.97	-3.89	1	25.86	25.86
3	22.05	-4	1	26.05	26.05
4	22	-4.09	1	26.09	26.09
5	22.22	-4.11	1	26.33	26.33
6	22.35	-4.13	1	26.48	26.48

7	22.38	-4.13	1	26.51	26.51
8	22.26	-4.14	1	26.4	26.4
9	22.07	-4.24	1	26.31	26.31
10	21.8	-4.36	1	26.16	26.16
11	21.47	-4.21	1	25.68	25.68
12	21.38	-4.12	1	25.5	25.5
13	21.41	-4.11	1	25.52	25.52
14	21.49	-4.05	1	25.54	25.54
15	21.49	-4.02	1	25.51	25.51
16	21.39	-4.02	1	25.41	25.41
17	4	-4.05	1	8.05	8.05
18	1.41	-4.03	1	5.44	5.44
			Total Area		450.9

Kentucky Ave # 1

X	Y1	Y2	Width	Height	Area
0	1.8	-2.2	1	4	4
1	2.3	-1.6	1	3.9	3.9
2	6.1	-2.4	1	8.5	8.5
3	8.8	-2.2	1	11	11
4	10.9	-2.2	1	13.1	13.1
5	11.3	-1.6	1	12.9	12.9
6	11.7	-1.3	1	13	13
7	11.3	-1.6	1	12.9	12.9
8	11.4	-1.7	1	13.1	13.1
9	11.7	-1.7	1	13.4	13.4
10	11.8	-1.8	1	13.6	13.6
11	11.6	-2.3	1	13.9	13.9
12	11.6	-2.3	1	13.9	13.9
13	11.6	-2.6	1	14.2	14.2
14	11.5	-2.4	1	13.9	13.9
15	11.8	-2.5	1	14.3	14.3
16	12.2	-1.6	1	13.8	13.8
17	12	-1.8	1	13.8	13.8
18	12.2	-3.2	1	15.4	15.4
19	12	-3	1	15	15
20	11.5	-3.2	1	14.7	14.7
21	11.7	-3.1	1	14.8	14.8
22	11.7	-3	1	14.7	14.7
23	11.1	-3.2	1	14.3	14.3
24	11.3	-3.3	1	14.6	14.6
25	11	-3.2	1	14.2	14.2
26	11.2	-3.1	1	14.3	14.3
27	11.3	-3.1	1	14.4	14.4
28	11.4	-3.1	1	14.5	14.5
29	11.3	-3.2	1	14.5	14.5
30	11.5	-3.1	1	14.6	14.6
31	11.1	-3.2	1	14.3	14.3
32	11.2	-3.1	1	14.3	14.3
33	11.3	-2.4	1	13.7	13.7
34	11.2	-2.3	1	13.5	13.5
35	11.4	-1.8	1	13.2	13.2
36	11.1	-1.7	1	12.8	12.8

37	10.6	-1.6	1	12.2	12.2
38	4.7	-2	1	6.7	6.7
			Total Area		507.9

Kentucky Ave #2

X	Y1	Y2	X adjusted		Width	Height	Area
-7	13.5	8	1		1	5.5	5.5
-6	13.5	8	2		1	5.5	5.5
-5	14	7.5	3		1	6.5	6.5
-4	14	7.5	4		1	6.5	6.5
-3	14.5	7	5		1	7.5	7.5
-2	14.5	7	6		1	7.5	7.5
-1	14.5	7	7		1	7.5	7.5
0	14.5	-2.5	8		1	17	17
1	14.3	-5.3	9		1	19.6	19.6
2	15	-5.5	10		1	20.5	20.5
3	14.7	-5.5	11		1	20.2	20.2
4	15	-5.3	12		1	20.3	20.3
5	15.1	-5.4	13		1	20.5	20.5
6	15	-5.3	14		1	20.3	20.3
7	15.1	-5.2	15		1	20.3	20.3
8	15.3	-5	16		1	20.3	20.3
9	15.3	-5.1	17		1	20.4	20.4
10	16.6	-5.1	18		1	21.7	21.7
11	16.9	-5	19		1	21.9	21.9
12	16.1	-5.1	20		1	21.2	21.2
13	15.1	-5.2	21		1	20.3	20.3
14	15.8	-5.3	22		1	21.1	21.1
15	15	-5.2	23		1	20.2	20.2
16	15	-5.2	24		1	20.2	20.2
17	15	-5.3	25		1	20.3	20.3
18	14.9	-5.4	26		1	20.3	20.3
19	14.8	-5.4	27		1	20.2	20.2
20	14.8	-5.5	28		1	20.3	20.3
21	14.5	-4.9	29		1	19.4	19.4
22	14.3	-4	30		1	18.3	18.3
23	14	-3.4	31		1	17.4	17.4
24	13.5	-2.2	32		1	15.7	15.7
25	13.4	-2.3	33		1	15.7	15.7
26	13.3	-2.3	34		1	15.6	15.6
27	12.6	-2	35		1	14.6	14.6
					Total Area		590.3

Appendix C: Kaemper’s 1908 Mammoth Cave Map